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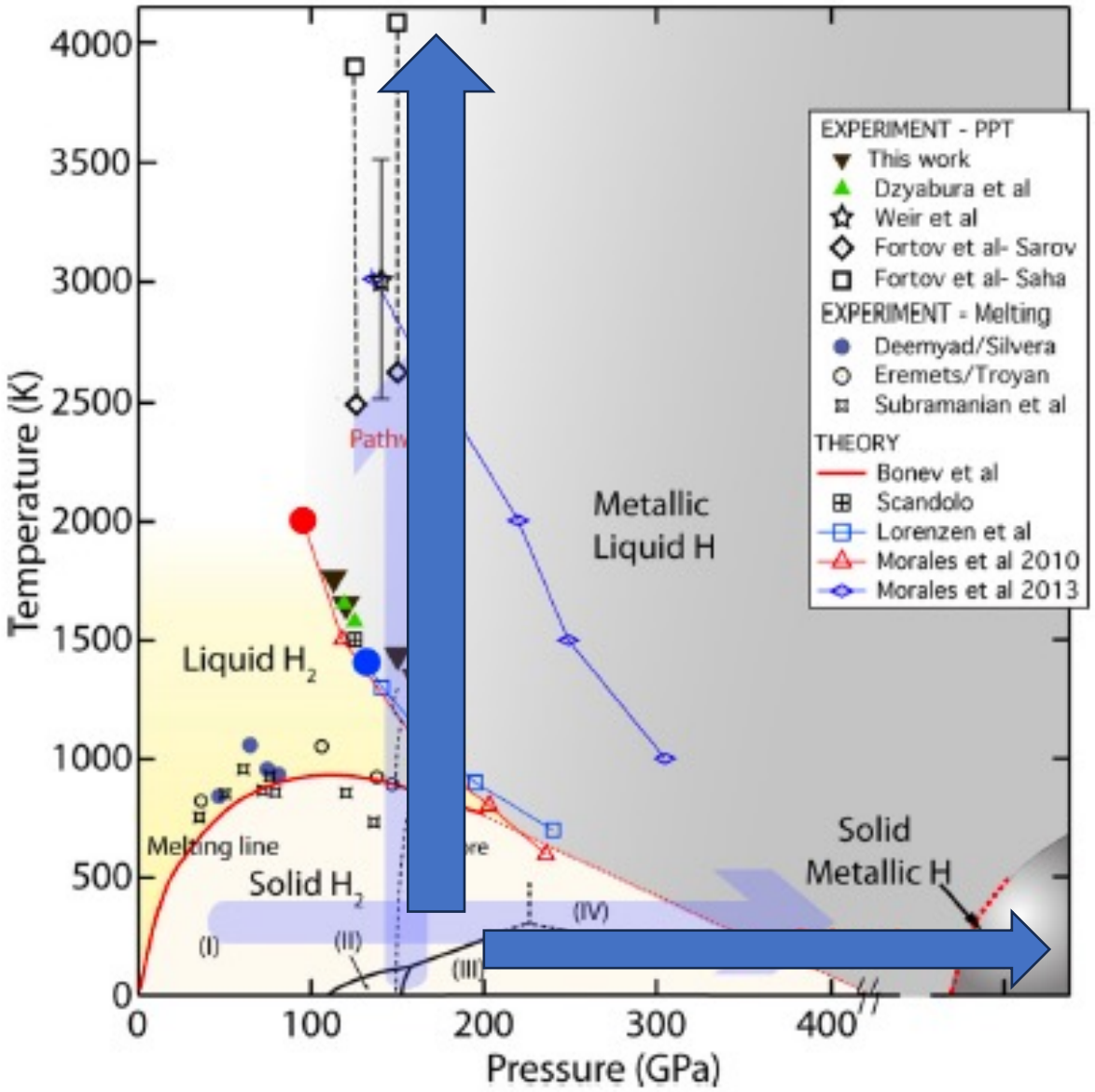
Making Metallic Hydrogen:
Holy grail of extreme condensed matter physics



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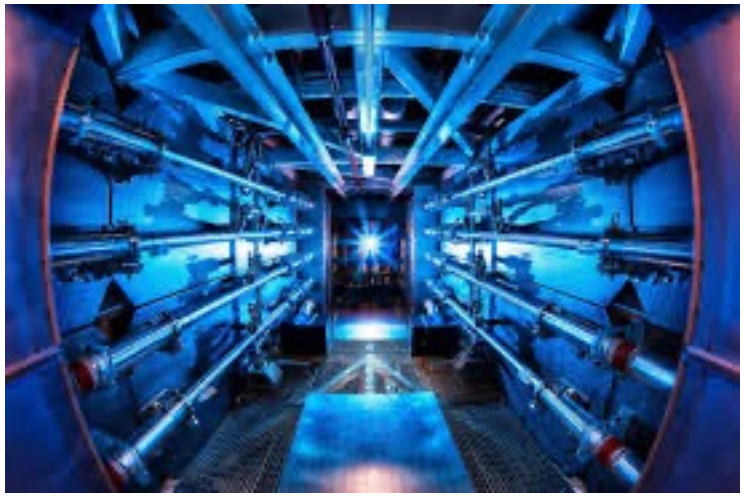
Race to make Metallic Hydrogen: Room Temperature superconductor, Holy grail of extreme condensed matter physics

Harvard group: Isaac Silvera

Dias and Salamat both postdocs in Ike's group at the same time



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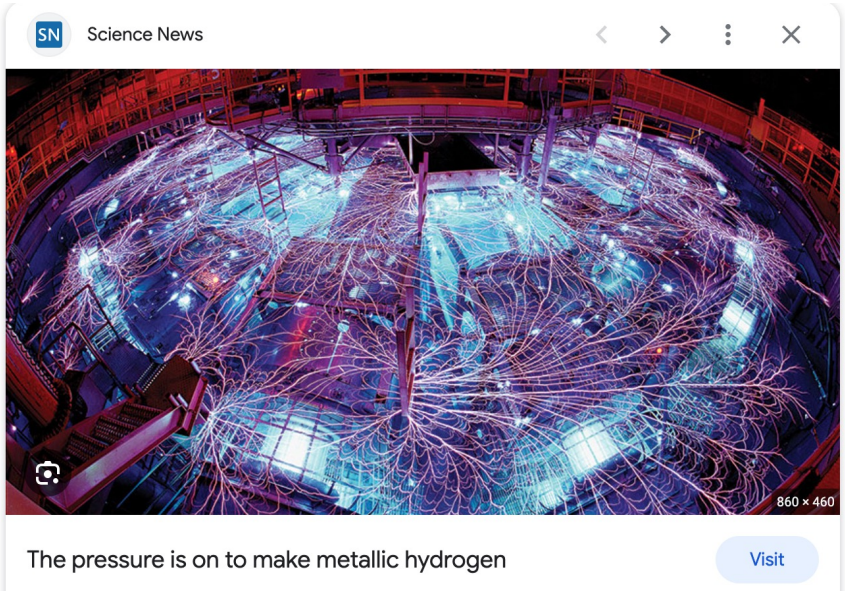

Sandia National Labs

Other main competitors

- Germany
- France
- UK
- China

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Harvard Group

PHYSICAL REVIEW B 93, 155128 (2016)

Evidence of a first-order phase transition to metallic hydrogen

Mohamed Zaghoo, Ashkan Salamat, and Isaac F. Silvera
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 25 March 2015; revised manuscript received 18 February 2016; published 15 April 2016)

The insulator-metal transition in hydrogen is one of the most outstanding problems in condensed-matter physics. The high-pressure metallic phase is now predicted to be liquid atomic from the low-temperature limit with the system in the ground state to very high temperatures. We have conducted measurements of optical properties of hot dense hydrogen in the region of 1.1–1.7 Mbars and up to 2200 K. We present evidence supportive of a first-order phase transition accompanied by changes in transmittance and reflectance, characteristic of a metal. The phase line of this transition has a negative slope in agreement with theories of the so-called plasma phase transition.

DOI: 10.1103/PhysRevB.93.155128

I. INTRODUCTION

Theory and experiment have worked closely together for decades on the problem of metallic hydrogen. In 1935, 80 years

hydrogen melts to liquid MH. At lower pressures and higher temperatures it is predicted to have a critical point so that for pressures below the critical pressure, the dissociative transition is continuous. The PPT is a Mott transition to a metallic liquid

RESEARCH

HIGH-PRESSURE PHYSICS

Observation of the Wigner-Huntington transition to metallic hydrogen

Ranga P. Dias and Isaac F. Silvera*

Producing metallic hydrogen has been a great challenge in condensed matter physics. Metallic hydrogen may be a room-temperature superconductor and metastable when the pressure is released and could have an important impact on energy and rocketry. We have studied solid molecular hydrogen under pressure at low temperatures. At a pressure of 495 gigapascals, hydrogen becomes metallic, with reflectivity as high as 0.91. We fit the reflectance using a Drude free-electron model to determine the plasma frequency of 32.5 ± 2.1 electron volts at a temperature of 5.5 kelvin, with a corresponding electron carrier density of 7.7 ± 1.1 × 10^{23} particles per cubic centimeter, which is consistent with theoretical estimates of the atomic density. The properties are those of an atomic metal. We have produced the Wigner-Huntington dissociative transition to atomic metallic hydrogen in the laboratory.

Several key problems in physics involving hydrogen include production of the metallic phase, high-temperature superconductivity, and controlled nuclear fusion (*1*). The transition to solid metallic hydrogen (SMH) was envisioned by Wigner and Huntington

The pathways to MH require either increasing pressure at low temperature (Fig. 1, pathway I) or increasing temperature to cross the plasma phase transition (Fig. 1, pathway II) (*12*–*17*). Pathway I transitions through a number of phases not envisioned in the simple phase diagram pre-

low temperatures. We maintained the sample at liquid-nitrogen or liquid-helium temperatures during the experimental runs. Alumina is also known to act as a diffusion barrier against hydrogen. We coated the diamonds along with the mounted rhenium (Re) gasket with a 50-nm-thick layer of amorphous alumina through the process of atomic layer deposition. We have found through our extensive experience with alumina coatings at high pressures that it does not affect or contaminate the sample, even at temperatures as high as ~2000 K (*12*). Last, focused laser beams, even at low laser power (10 mW) on samples at high pressures in DACs, can also lead to failure of the highly stressed diamonds. Laser light in the blue spectral region appears to be particularly hazardous because it potentially induces the growth of defects (*27*). Thermal shock to the stressed culet region from inadvertent laser heating is another risk. Moreover, a sufficiently intense laser beam, even at infrared (IR) wavelengths, can graphitize the surface of the diamond. Thus, we studied the sample mainly with very low-power, incoherent IR radiation from a thermal source and minimized illumination of the sample with lasers when the sample was at very high pressures.

We cryogenically loaded the sample chamber at 15 K, which included a ruby grain for pressure determination. We initially determined a pressure of ~88 GPa by means of ruby fluorescence (*26*). Determining the pressure in the megabar regime is more challenging (*26*). We

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Harvard group: Isaac Silvera, Ranga Dias

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NIF / LLNL

NIF/LLNL: Leading team members

Marius Millot and Peter Celliers

HIGH-PRESSURE PHYSICS

Insulator-metal transition in dense fluid deuterium

Peter M. Celliers[1]*, Marius Millot[1], Stephanie Brygoo[2], R. Stewart McWilliams[3], Dayne E. Fratanduono[1], J. Ryan Rygg[1,4], Alexander F. Goncharov[5], Paul Loubeyre[2], Jon H. Eggert[1], J. Luc Peterson[1], Nathan B. Meezan[1], Sebastien Le Pape[1], Gilbert W. Collins[1,4], Raymond Jeanloz[6], Russell J. Hemley[7]

Dense fluid metallic hydrogen occupies the interiors of Jupiter, Saturn, and many extrasolar planets, where pressures reach millions of atmospheres. Planetary structure models must describe accurately the transition from the outer molecular envelopes to the interior metallic regions. We report optical measurements of dynamically compressed fluid deuterium to 600 gigapascals (GPa) that reveal an increasing refractive index, the onset of absorption of visible light near 150 GPa, and a transition to metal-like reflectivity (exceeding 30%) near 200 GPa, all at temperatures below 2000 kelvin. Our measurements and analysis address existing discrepancies between static and dynamic experiments for the insulator-metal transition in dense fluid hydrogen isotopes. They also provide new benchmarks for the theoretical calculations used to construct planetary models.

The transformation of hydrogen from a molecular insulator to an atomic metal at high densities has been a longstanding focus in physics and planetary science (*1*). The unique quantum metallic properties of the low-temperature solid (i.e., below 300 K) have drawn sustained interest (*2*–*5*), and characterizing the transformation in the hot, dense fluid is crucial for understanding the internal structure and dynamics of giant planets (*6*), including properties below 2000 K and up to several hundred GPa.

Dynamic compression can explore a broad range of thermodynamic paths with time-varying manipulations of the applied pressure and controlled reverberation of pressure waves through the sample. This includes probing the dense fluid at temperatures below 2000 K, for example, with an initial jump in pressure delivered by a shock wave followed by shock reverberation on gradual

the choice of exchange-correlation functional used and whether zero-point energy is accounted for (*1*, *16*). Quantum Monte Carlo (QMC) calculations should provide improved bounds on the transition pressures (*16*, *17*), although they disagree with a recent benchmarking experiment (*30*). Transition pressures for hydrogen and deuterium are expected to be different because of isotope effects, but with a small relative magnitude. The transition in deuterium from QMC simulations is 30 GPa higher than in hydrogen at 600 K, decreasing to 10 GPa higher at 1200 K (*16*). Despite experimental support for a first-order IM transition (*19*, *20*, *22*, *23*), the critical point has not been experimentally identified. Furthermore, the broad discrepancies in the measured transition pressure (*20*, *22*, *23*) and character (*20*–*23*) have made resolving the differences between the theoretical models challenging.

We completed a series of five dynamic compression experiments at the National Ignition Facility (NIF) to probe the IM transition up to 600 GPa at temperatures ranging from 900 K to 1600 K. The experiments were carried out using 168 laser beams to deliver up to 300 kJ of ultraviolet light that drove a near-isentropic reverberation compression of a cryogenic liquid deuterium sample. We adjusted the time dependence of the laser delivery (pulse shape) to control the compression sequence imposed on the sample as a function of time. Line-imaging Doppler velocimetry recorded both the compression history and the evolution of the optical properties of the D_2 sample during the nanosecond compression

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Sandia lab:
Leading team member
Marcus Knudson

HIGH-PRESSURE PHYSICS

Direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium

M. D. Knudson,[1]* M. P. Desjarlais,[1] A. Becker,[2] R. W. Lemke,[1] K. R. Cochrane,[1] M. E. Savage,[1] D. E. Bliss,[1] T. R. Mattsson,[1] R. Redmer[2]

Eighty years ago, it was proposed that solid hydrogen would become metallic at sufficiently high density. Despite numerous investigations, this transition has not yet been experimentally observed. More recently, there has been much interest in the analog of this predicted metallic transition in the dense liquid, due to its relevance to planetary science. Here, we show direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium. Experimental determination of the location of this transition provides a much-needed benchmark for theory and may constrain the region of hydrogen-helium immiscibility and the boundary-layer pressure in standard models of the internal structure of gas-giant planets.

In 1935, Wigner and Huntington (*1*) were the first to predict that when squeezed to sufficiently high density (ρ) and pressure (*P*), hydrogen would undergo a density-driven transition from an insulating, molecular solid to a conducting, atomic solid. Subsequently, this fundamental question of precisely how and at what *P* hydrogen metallizes at low temperature (*T*) has become one of the longest-standing open questions of high-pressure physics (*2*). More recently, there has been much interest in the analogous molecular insulator to atomic metal transition in the liquid at low *T* just above the melt line, largely due to its relevance to planetary science (*3*, *4*). A metallization transition in this region could provide a constraint for the

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